base, transit through the base, and then tunnel through the tunnel barrier at the collector/base interface and then enter the collector.

[0014] The flow of electrons from emitter to base is controlled in both types by varying the emitter/base barrier potential by means of an applied voltage V_{eb}. The flow of electrons from the base to the collector can is made favorable by means of an externally applied voltage V_{bc} between base and collector. Under normal operating conditions, V_{bc} reverse biases the base/collector junction. Electrons injected from the emitter into the base have energy substantially greater than the thermal energy of the ambient electrons in the base. These "hot" electrons ideally traverse the base without undergoing significant scattering. If the barrier at the base/collector interface is lower than the hot electron energy, then some of the hot electrons can cross the barrier, be transmitted through the depletion region of the collector, and enter the sea of conduction electrons in the collector.

[0015] One of the critical parameters for transistors is the base resistance. A low base resistance is important to achieve a high maximum frequency of oscillation, fmax.

[0016] Graphene is a monolayer of conjugated sp^2 bonded carbon atoms tightly packed into a two-dimensional (2D) hexagonal lattice. One of the primary advantages of graphene is that it has extremely high intrinsic carrier (electron and hole) mobility and thus has extremely high electric conductivity. Graphene has the potential to have the highest conductivity and lowest resistivity of any material, with a conductivity even higher than that of silver. See Chen et al., "Intrinsic and extrinsic performance limits of graphene devices on SiO_2," *Nature Nanotechnology* 3, 206-209 (2008).

[0017] For example, experimental results indicate that the resistivity of a single sheet of graphene approximately 3 angstrom thick grown on the silicon face of SiC has a sheet resistance on the order of 750 ohm/square to 1000 ohms/square, while a graphene sheet grown on the surface of copper can have a sheet resistance of approximately 1200 to 1500 ohms/square. In some cases, the sheet resistance of few sheets of graphene can be even less, as little as 100 ohms/square. Chen et al., supra.

[0018] The high electrical conductivity of graphene allows the use of a extremely thin graphene material base layer, even one comprising only a single graphene sheets and having a thickness of approximately 0.28 nm for a single sheet of graphene.

[0019] Use of such a thin graphene base layer reduces the transit time of electrons through the base layer and also reduces the energy loss of hot electrons in transiting the thin graphene base material. In addition, the high velocity of electrons in the graphene material can lower the base transit time. Thus, the semiconductor device with a graphene material base layer can have high fT and high fmax.

SUMMARY

[0020] This summary is intended to introduce, in simplified form, a selection of concepts that are further described in the Detailed Description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter. Instead, it is merely presented as a brief overview of the subject matter described and claimed herein.

[0021] The present invention provides a transistor device having a graphene base for controlling the transport of electrons from the emitter to a collector.

[0022] The transistor of the present invention consists of a heterostructure comprising an electron emitter, an electron collector, and a graphene material base layer consisting of one or more sheets of graphene situated between the emitter and the collector. The emitter typically contacts a first surface of the graphene material base layer to form an emitter/base interface. The collector typically contacts the graphene material base layer at a second surface thereof opposite the first surface to form a base/collector interface.

[0023] The graphene material base layer can be either an N-type graphene material or a P-type graphene material or a combination of N-type and P-type graphene material.

[0024] In some embodiments, the emitter contains an emitter transition layer disposed at the emitter interface with the graphene material base layer (emitter/base interface).

[0025] In some embodiments, the collector contains a collector transition layer disposed at the collector interface with the graphene material base layer and the collector (collector/base interface) to facilitate the collection of electrons that transit the graphene material base layer into the collector and to allow a voltage to be applied between the graphene base material layer and the N-type collector.

[0026] In the case of non-hot electron injection, the material used for the collector should have a potential that is lower than that of the graphene material base layer so that there is not a potential barrier at the transition layer between the base layer and the collector. Materials that can be used for the collector in such cases include CdSe, InAs, SnO2: F, InSb, ZnO, BN, CdTe, CdS, In2O3:Sn, InGaN, InAsP, InP, InGaAs, InAlAs, InGaSb, and diamond.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] FIGS. **1**A and **1**B depict aspects of a general exemplary embodiment of a transistor having a graphene base in accordance with the present invention.

[0028] FIGS. **2**A-**2**F depict conduction band minimum diagrams and barriers for hot electron injection for various exemplary embodiments of a transistor having a graphene base in accordance with one or more aspects of the present invention

[0029] FIGS. **3**A and **3**B depict conduction band minimum diagrams for non-hot electron graphene base transistors.

[0030] FIG. **4** depicts aspects of a processor the formation of a transferred and bonded graphene material base layer used in a graphene base transistor in accordance with the present invention.

[0031] FIGS. **5**A-**5**B depict aspects of an exemplary embodiment of a hot electron transistor having a graphene base in accordance with the present invention.

[0032] FIGS. **6**A-**6**B depict aspects of a second exemplary embodiment of a hot electron transistor having a graphene base in accordance with the present invention.

[0033] FIGS. **7**A-**7**B depict aspects of a third exemplary embodiment of a hot electron transistor having a graphene base in accordance with the present invention.

[0034] FIGS. **8**A-**8**B depict aspects of a fourth exemplary embodiment of a hot electron transistor having a graphene base in accordance with the present invention.

[0035] FIGS. **9**A-**9**B depict aspects of a fifth exemplary embodiment of a hot electron transistor having a graphene base in accordance with the present invention.